Recurrent Geomagnetic Storms and the Solar Wind

Joan Hirshberg

National Aeronautics and Space Administration
Space Sciences Division
Ames Research Center, Moffett Field, California

Abstract

The structure that would be expected to develop when a fast stream in the solar wind is embedded in a slower ambient wind is discussed on the basis of gas dynamics. This structure is compared to that appearing in recurrent geomagnetic storms. It is found that the development of M region storms follows the expected structure of the solar wind stream. The sudden commencements on some M storms correspond to the shock that is expected to occur in the solar wind if the relative velocities of the fast stream face and the ambient wind are high enough. It is also shown that the typical quiet initial phase of the s.c. M storm corresponds to the relatively low velocity region in space between the shock and the stream proper. The main phase corresponds to the high velocity stream itself. In particular the fast M streams detected by Mariner 2 and their associated geomagnetic storms are discussed.

1. Introduction

It is well established that geomagnetic storms are caused by the effects of the solar wind as it impinges on the magnetic field of the earth. Although storms are thus explained in broad outline, the details of the process are still very poorly understood. Recently, an important step was taken when an analysis of the data from the plasma probe on Mariner 2 [Snyder, Neugebauer, and Rao, 1963] showed that recurrent series of geomagnetic storms corresponded to the appearance at the earth of streams of relatively high velocity solar plasma. The purpose of this paper is to examine the expected structure of these streams as this structure relates to the development of the geomagnetic storms on the surface of the earth. It has recently been pointed out by Mustel' [1964] that M region storms often have sudden commencements. Thus, the archetype of geomagnetic storms can be described in terms of a sudden commencement, an initial phase during which the intensity of the horizontal component of the surface field remains relatively high, and a main phase with a depressed and disturbed magnetic field. No completely satisfactory theory of the main phase exists. It is of interest to ask if this storm structure must be due primarily to processes occurring within the magnetosphere, or if it may be due directly to the structure of the impinging solar plasma stream.

In Section 2 below, the expected structure of the plasma stream is described on the basis of a gas dynamic model, Section 3 deals with the relationship of this structure to the development of the geomagnetic storm.

2. The Structure of the Streaming Plasma

In this section the M region plasma stream will be discussed on the basis of gas dynamics. Surface magnetic observations of M region storms indicate that the M region stream lasts for many months, or even years [Sinno, 1956; Tandon, 1956]. Five successive recurrences of a single high velocity stream have actually been observed in space [Snyder, Neugebauer, and Rao, 1963]. Thus, the steady state that will be reached by the high velocity stream imbedded in a relatively low velocity solar wind will be described.

The results of gas dynamics will be used. This approach has been remarkably successful in describing the interaction of the solar wind with the obstacle presented by the earth's dipole field [Wolfe and Silva, 1964; Bridge et al., 1964; Ness, 1964]. Since, in this paper, we are interested in gross characteristics only, such as the existence or nonexistence of shocks, it is expected that the corrections that would appear in a more exact approach will not significantly alter the discussion. The reader is referred to Landau and Lifshitz [1959] for derivations of the results presented in this section.

As the high velocity stream advances into the interplanetary region the leading edge of the stream forms a spiral which may be described by a hose angle in the same way as the magnetic field direction [Chapman and Bartels, 1940; Parker, 1963],

$$\alpha = \arctan \frac{r\Omega}{v}$$

where α is the inclination of the stream front to the radial direction, v is the plasma velocity, r is the distance from the sun, and Ω is the solar angular velocity. Since the hose angle depends on velocity, it will be different for the quiescent plasma and for the high velocity plasma. As a result, fast and slow streams of plasma will come into collision with one another, the faster stream advancing into the slower plasma [Parker, 1963]. If two masses of gas come into collision at high enough relative velocities, shocks and a tangential discontinuity will form at the boundary between the two gases [Landau and Lifshitz, 1959; Dessler and Fejer, 1963].

The front of the fast stream advances into the slower quiescent plasma with a velocity given by

$$V_R = (V - v)\sin \alpha$$

where V_R is the relative velocity of the plasma front in a direction normal to the face of the fast stream, V and v are the streaming velocities of the fast and quiescent plasmas, respectively, and α is the hose angle appropriate to the enhanced stream. The coordinate system is one in which the observer is at rest with respect to the sun. If V_R is supersonic, a shock will form.

The plasma measurements made by Mariner 2 indicated that the velocities of the quiescent plasma were in the range of 300 to 500 km/sec while enhanced plasma velocities are known from sudden commencement storm studies to range to above 1000 km/sec. Figure 1 shows the relative velocities V_R, for a range of quiescent and enhanced velocities. Since the sound speed in the plasma is of the order of 50 km/sec, the relative velocity can become supersonic, and shocks and a tangential discontinuity will form.

Figure 1

We note that the boundary conditions at a shock permit a sudden change of pressure across the shock, as well as a change in the normal component of the velocity. The tangential components of the velocity are continuous across the shock and there is a mass flux across it. At the tangential discontinuity, where the two streams of gas come together, there is no mass flux, and the pressures on either side of the discontinuity are equal. However, as the name of this discontinuity implies, any change in the tangential component of the velocity is permitted.

The fast M region stream imbedded in a quiescent gas is a steady-state problem. In order to be able to describe the structure of the stream as it will appear after several months we must see how the various discontinuities will evolve in time; that is, in the steady state, where will the two shocks be relative to the surface of contact between the two streams of gas?

An observer at rest with respect to the tangential discontinuity will observe gas flowing across both shocks toward the tangential discontinuity. See Figure 2. If this material has nowhere to go, the shock will move farther away from the tangential discontinuity. Figure 2
Thus, if the front of the stream were a plane, the shocks would move farther and farther away from the contact surface. However, for a nonplanar front to the stream, the shock will move away from the contact surface until an equilibrium standoff distance is reached, where the amount of material that flows in across the shock is equal to the amount that flows out of the standoff region. Now, when material passes through the shock the stream lines are bent toward the shock as shown in Figure 2 [Landau and Lifshitz, 1959]. In the case of a convex surface the stream lines diverge and the material flows around the object and a steady-state shock standoff distance exists. The standoff distance depends on the radius of curvature of the front and on the Mach number [Hayes and Probstein, 1959]. The curvature of the stream face referred to occurs in the

plane perpendicular to the ecliptic. No equilibrium distance exists for a shock parallel to a concave surface. Therefore, in the steady-state M stream there will not be a shock parallel to the stream front in the fast stream.

The relations between the structure of the fast stream and the events that make up an M region magnetic storm are to be discussed. The structure will be summarized below as it will be seen from the earth as the stream sweeps across. Particular emphasis will be put on those variables that are related to surface magnetic events.

a. The first change that occurs as the stream approaches the earth is the arrival of the shock that precedes the stream. There is a sudden change in pressure, velocity, and density across the shock. Note that the shock will only exist if the relative velocities are sufficiently high.

b. The earth then enters the standoff region. The pressure and density remain high. The velocity is made up of two major components, the streaming velocity of the undisturbed quiescent plasma plus the flow out of the way of the advancing nose of the fast stream. Near the nose of the fast stream the plasma in the standoff region will be pushed forward with the velocity of the fast front. The width of the standoff region depends on the shape of the front of the enhanced plasma stream and on the Mach number.

c. The tangential discontinuity appears at the end of the standoff region. There is no change of pressure at this point, but there is a change in velocity, to that of the radially streaming fast plasma. The density may change by any amount. This discontinuity is highly unstable in gas dynamics and unless stabilized by the presence of a magnetic field will be broadened into a turbulent transition region. This region will exist even if the relative velocities of the stream and the quiescent plasma are not high enough to cause a shock to form.

d. The enhanced stream proper now appears.

It has been suggested [Sarabhai, 1963], on the basis of a particle picture, that a cavity would appear behind the M stream. In a gas dynamical picture, such a cavity would not form. The conditions behind the stream will be very complex and no attempt will be made to describe them.

3. Comparison With Geomagnetic Storms

In this section, the effects of these discontinuities and regions on surface magnetic variations are discussed. It is considered that a sudden increase in the product of the density and the square of the velocity will cause a sudden decrease in the size of the earth's magnetosphere, and a surface sudden commencement. Also, it is assumed that high plasma velocity is associated with high values of surface magnetic disturbance index, Ap [Snyder et al., 1963]. No assumptions are made as to the physical causes of this association.

The paragraphs below are numbered to correspond with the regions and discontinuities listed above.

a. The Shock. The shock corresponds to a sudden commencement. Thus, if the relative velocity of the two streams is high enough, an M stream storm should have an s.c. In order to search for these sudden commencements the musical diagrams [Bartels and Veldkamp, 1950-1956] were examined for the years 1950 to 1955. During that period there were 58 geomagnetic storms that clearly belonged to well-defined recurrent series. The musical diagrams indicated that 20 of the disturbances began with sudden commencements, while 38 did not. Figure 3 shows the musical diagrams for an outstanding series in 1953. A small triangle indicates a sudden commencement. Note that some recurrences exhibited sudden commencements while others did not. Figure 4 shows the onset of three storms of this series as observed at Honolulu. Note that the sudden commencements are small and are followed by quiet initial phases of several hours duration. These small s.c.'s and quiet initial phases are characteristic of the sudden commencements associated with recurrent storm series.

Figure 3

Figure 4

Recurrent geomagnetic storms, or M region storms, are sometimes referred to as nonsudden-commencement storms. The reason for this misnomer is historical. Interest was originally centered on the problem of finding the differences between storms that started with a sudden commencement and those that did not. When storms were divided according to that criterion it was found that the nonsudden-commencement storms recurred with each rotation of the sun, while sudden commencement storms did not [Mustel', 1957]. However, this is a statistical result. If the question is turned around, and storms are divided into two groups on the basis of their recurrence characteristics, we can then ask about the character of the storm onset for these groups. It is found that nonrecurrent storms begin with sudden commencements, while recurrent storms sometimes show a sudden commencement and sometimes do not [Mustel', 1964].

Figure 5 again shows the velocity of the fast plasma front relative to the quiescent plasma for various values of the streaming velocities. Included in this figure are circles corresponding to the values measured by the Mariner 2 plasma probe for the streams present during Mariner's flight [Snyder, Neugebauer, and Rao, 1963]. Each circle corresponds to the appearance of a stream of high velocity plasma. The correlation between high velocities in the solar wind and high values of K_p was excellent during the flight of Mariner 2. The shaded circles correspond to M storms for which 10 or more surface magnetic stations reported a sudden commencement. The open circles are cases in which few or no stations reported sudden commencements [Lincoln, 1963]. The half shaded circle is a doubtful case in which the sudden commencement appeared on the surface about a half day to a day earlier than expected. Note that 4 or 5 out of 6 cases in which the relative velocity was greater than 125 km/sec showed a sudden commencement while 1 out of 11 cases showed a sudden commencement for lower relative velocities. The relative velocity in many of the slower cases is still supersonic. However, the Mach number is low, the standoff distance is large, and

Figure 5

the changes at the shock are small. Thus, the shock would be relatively weak and will occur long before the gradual onset of the storm.

The lowest velocity point associated with a sudden commencement must be discussed further. It corresponds to a sudden commencement reported by 46 stations on the surface of the earth. The storm must have been related to some event in space but the change in daily mean plasma velocity at Mariner 2 was not enough to cause it. Because of this, the detailed data from Mariner 2 were examined. (The author would like to thank Conway W. Snyder and Marcia Neugebauer for supplying the data prior to publication.)

If the surface magnetic event were associated with an M region stream, then the positions of the earth and Mariner 2 and the velocity of the solar wind were such that the events should have appeared at the space probe and on the surface of the earth at about the same time. There is no evidence for any velocity changes at that time large enough to correspond to an M region stream shock.

On the other hand, if the surface magnetic event were associated with an impulsive event, such as a flare on the sun, the disturbance would be traveling radially outward and would arrive at Mariner 2 one day earlier than on the surface of the earth. The Mariner 2 data were examined for this period as well. No velocity changes of any consequence were found. However, a large peak in number density did occur at about the proper time [Neugebauer and Snyder, 1964]. The number density increased fourfold some 20 hours before the surface event. If this density change could maintain itself and steepen as it propagated outward during the next 20 hours, it could cause the s.c. without any velocity change in the wind. The only other possibility that exists is that the event on the earth's surface was caused by variations in solar wind parameters that were of sufficiently small spatial extent that the "cloud" hit the earth, but missed Mariner altogether.

In interpreting this event, it should be kept in mind that not every s.c. must be caused by an M region and the arrival of a very weak M stream and a rather strong s.c. at more or less the same time is most likely a chance occurrence, and that this point on Figure 5 is not necessarily a real disagreement.

b. The Standoff Region. The important parameters in this region are the velocity and the density. The magnetosphere remains compressed so that the surface horizontal field remains high. The velocity can be approximated by a superposition of the velocity of the undisturbed plasma and the velocity of the front of the enhanced stream. Figure 6 shows the velocity in the standoff region for a range of quiescent solar wind velocities and of enhanced stream velocities. Note that the velocity in the standoff region is not high. For example, for a quiescent wind of 300 km/sec the highest velocity expected is less than 500 km/sec. This corresponds to a most probable Ap of 12 [Snyder, Neugebauer, and Rao, 1963]. Thus we expect quiet initial phases as observed.

Figure 6

The existence of quiet initial phases has been very difficult to explain in the theory of geomagnetic storms. If all storms had quiet initial phases, then it would be a simple matter of finding a process in which the main phase took a long time to develop. On the other hand, if no initial phases were quiet then this would imply that the enhanced plasma had immediate effects. The difficulty is to explain the variability - some initial phases are quiet, some are not. It would be very satisfying if this difference could be explained as being due entirely to the low velocities in the standoff region of M storm streams since in the case of flare induced storms, the shock travels radially outward from the sun and the velocity in the standoff region will be comparable to the velocity of the plasma cloud itself. Thus, the initial phase of flare induced storms would not be expected to be quiet. However, an examination of the magnetograms published by the Coast and Geodetic Survey shows that not all quiet initial phases of sudden commencement storms belong to storms arising from stable M streams. Storms arising from M streams that last less than 3 or 4 solar rotations cannot be distinguished from flare associated storms by surface observations alone.

c.,d. The Turbulent Region and the Stream Proper. The magnetosphere next sees the turbulent region that forms the boundary between the enhanced stream and the quiescent stream. As this region crosses the earth the direction and velocity of the plasma change. The tail of the magnetosphere swings around and the magnetosphere size will change. The velocity increases gradually as the stream proper appears. This may correspond to the gradual onset of the main phase.

On the other hand, since the main phase processes are not understood, the gradual onset may also well be due to processes occurring within the magnetosphere.

4. The Thickness of the M Stream

The development of an M region storm, then, closely parallels the structure that would be expected to develop when a fast stream of plasma interacts with the slower ambient plasma. The standoff distance between the shock and the main stream depends on the radius of curvature of the face of the stream. The pertinent curvature is the curvature in plane perpendicular to the ecliptic.

A measurement of the standoff distance of the shock would permit an estimate of the radius of the nose of the stream. Now the shock arrives at the earth at the time of the sudden commencement, while the main phase does not develop until the earth is in the main stream. It cannot be assumed that the main phase develops as soon as the earth enters the main stream so that the length of the initial phase of the geomagnetic storm gives a maximum for the time of passage of the standoff region. If the onset of the main phase is fairly sharp, this time can be measured. To find the width of the standoff region further assumptions must be made as to the streaming velocities involved as well as the ratio of specific heats of the solar wind gas and the Mach number of the flow. Using quiescent wind velocities between 300 and 500 km/sec, enhanced velocities up to 1200 km/sec, a specific heat ratio of 5/3 and a

Mach number of the order of 4, it was found that, for a typical initial phase lasting 5 hours, the radius of curvature of the nose of the stream was of the order of 0.07 AU at the orbit of the earth. If it is then assumed that the cross section of the nose of the stream were somewhere near semicircular, the stream in the plane perpendicular to the ecliptic would have a width of the order of 8° at a distance of 1 AU from the sun [Hayes and Probstein, 1959]. The length of the initial phases of 22 M region sudden commencement storms ranged from 1-1/2 to 8 hours. The width of the streams can be estimated at from 2° to 14°. This agrees well with a width of 10° deduced from the semiannual variation in the appearance of M region storms [Sinno, 1956; Preister and Cattani, 1962]. Note that the length of the beam in the ecliptic plane is of the order of 45°, at the orbit of the earth.

5. Conclusions

It is found that the development of M region magnetic storms follows the structure expected from a fast stream of particles embedded in a slower solar wind. That is, the frequent appearance of sudden commencements on M storms corresponds to the development of shocks. The quiet initial phase reflects the low velocity standoff region. It was assumed that the development of the main phase is correlated with the velocity of the solar wind as shown by experiment. No particular mechanism was assumed to explain this correlation.

An estimate of the width of the M region in the meridian plane from the size of the standoff distance of the shock gave reasonable values.

Acknowledgements. I would like to thank Dr. John R. Spreiter for many helpful and interesting discussions. I am also grateful to Dr. Conway W. Snyder and Dr. Marcia Neugebauer for permission to quote their results prior to publication.

References

Bartels, J., and J. Veldkamp, Geomagnetic and solar data, J. Geophys. Res., 1950-1956.

Bridge, H. S., A. Egidi, A. Lazarus, E. F. Lyon, L. Jacobson, and R. H. Baker, Initial results from the first interplanetary monitoring platform (IMP-I), I. G. Bulletin, 84, June 1964.

Chapman, S., and J. Bartels, Geomagnetism, Oxford, Clarendon Press, 1940.

Dessler, A. J., and J. A. Fejer, Interpretation of K index and M-region geomegnetic storms, Planetary and Space Sci., II, 1963.

Hayes, Wallace D., and Ronald F. Probestein, Hypersonic Flow Theory, Academic Press, New York, 1959.

Landau, L. D., and E. M. Lifshitz, Fluid Mechanics, Pergamon Press, London, 1959.

Lincoln, Virginia, Geomagnetic and solar data, J. Geophys. Res., 68, (8) April 1963.

Lincoln, Virginia, Geomagnetic and solar data, J. Geophys. Res., 68, (12), June 1963.

Mustel', E. R., The physical nature of the differences between geomagnetic disturbances of sudden and nonsudden commencement, Soviet Astronomy, A. J., 1, Jan.-Feb. 1957.

Mustel', E. R., Solar corpuscular streams and geomagnetism, Astron. Z., 41, (5), 1964.

Ness, N. F., Initial results from the first interplanetary monitoring platform (IMP-I), I. G. Bulletin, 84, June 1964.

Neugebauer, Marcia, and Conway W. Snyder, presented at the Solar Wind Conference, Jet Propulsion Laboratory, April 1-4, 1964, will appear in book entitled The Solar Wind.

Parker, E. N., Interplanetary Dynamical Processes, Interscience Publishers, 1963.

Preister, W., and D. Cattani, On the semi-annual variation of geomagnetic activity and its relation to the solar corpuscular radiation, J. Atmos. Sci., 19, 121-126, 1962.

Sarabhai, Vikram, Some consequences of nonuniformity of solar wind velocity, J. Geophys. Res., 68, (5), March 1, 1963.

Snyder, Conway W., Marcia Neugebauer, and U. R. Rao, The solar wind velocity and its correlation with cosmic ray variations and with solar and geomagnetic activity, J. Geophys. Res., 68, (24), Dec. 15, 1963.

Sinno, K., On the origin of the long-lived solar corpuscular streams which appeared last solar cycle, 1950-1953, Rep. Ionos. Res., 10, Japan, 1956.

Tandon, J. N., A note on the annual variation of geomagnetic activity, J. Geophys. Res., 61, 1956.

Wolfe, J. H., and R. W. Silva, Initial results from the first interplanetary monitoring platform (IMP-I), I. G. Bulletin, 84, June 1964.

Figure Captions

Figure 1. The velocity of the front of the fast gas stream relative to the quiescent gas as a function of the velocity within the fast stream. Various values of velocity of quiescent gas are shown.

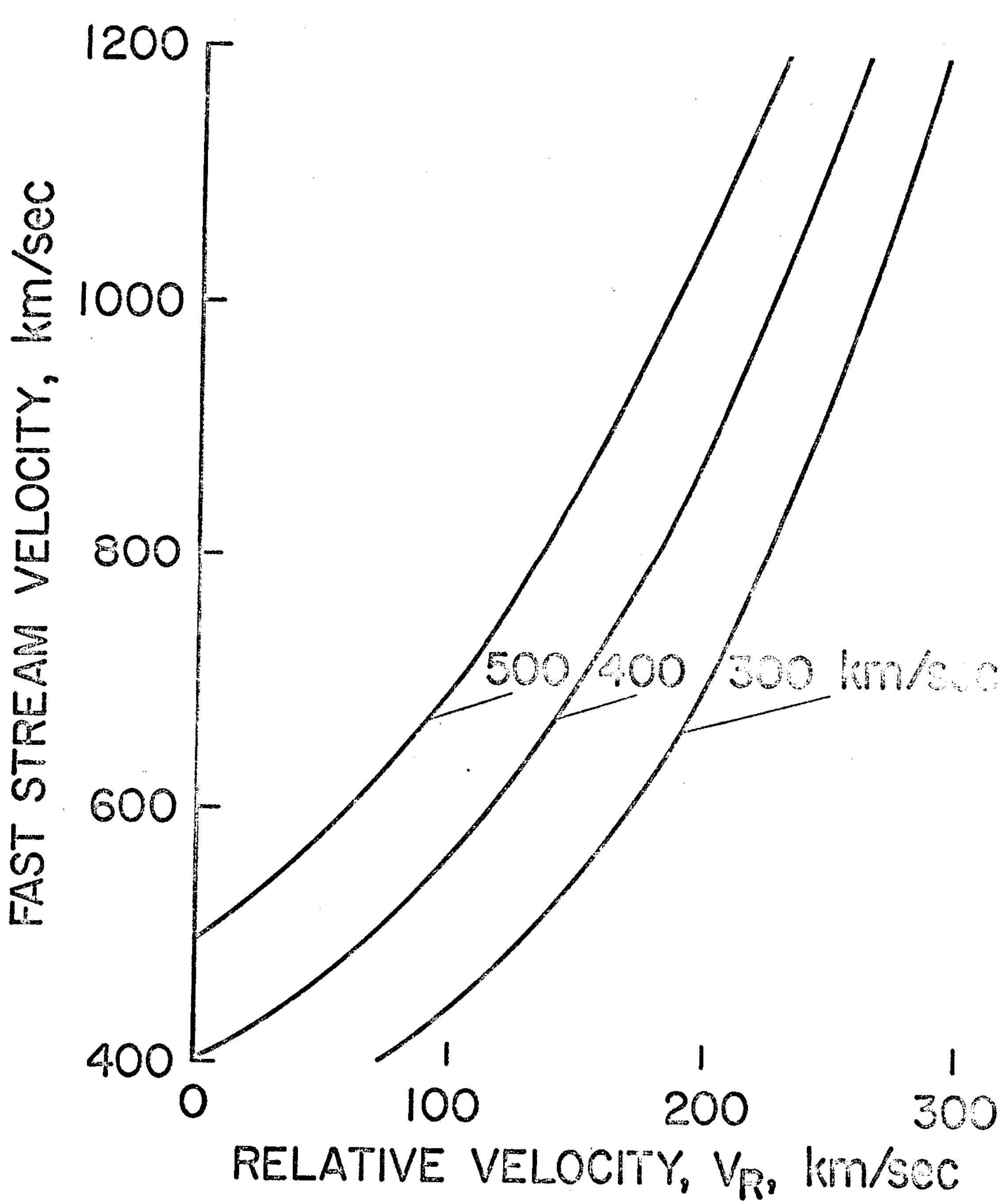
Figure 2. Idealized gas flow across the shocks that may form when two streams of gas come into contact.

Figure 3. Musical diagram showing a series of recurrent sudden commencement storms [Bartels and Veldkamp, 1954].

Figure 4. The Coast and Geodetic Survey magnetometer records from Honolulu showing 3 sudden commencement storms of the Figure 3 series. The fourth sudden commencement of the series was not discernible at Coast and Geodetic Survey stations.

Figure 5. M region streams observed by Mariner 2. The shaded circles correspond to streams associated with sudden commencements. The open circles correspond to streams not associated with sudden commencements. The half shaded point is a doubtful case.

Figure 6. The velocity in the standoff region as a function of the velocity of the M stream flow for various values of streaming velocity of the quiescent wind.



1200
1000
800
600
400
0
100
200
300
FAST STREAM VELOCITY, km/sec
RELATIVE VELOCITY, V_R, km/sec
500
400

Figure 1

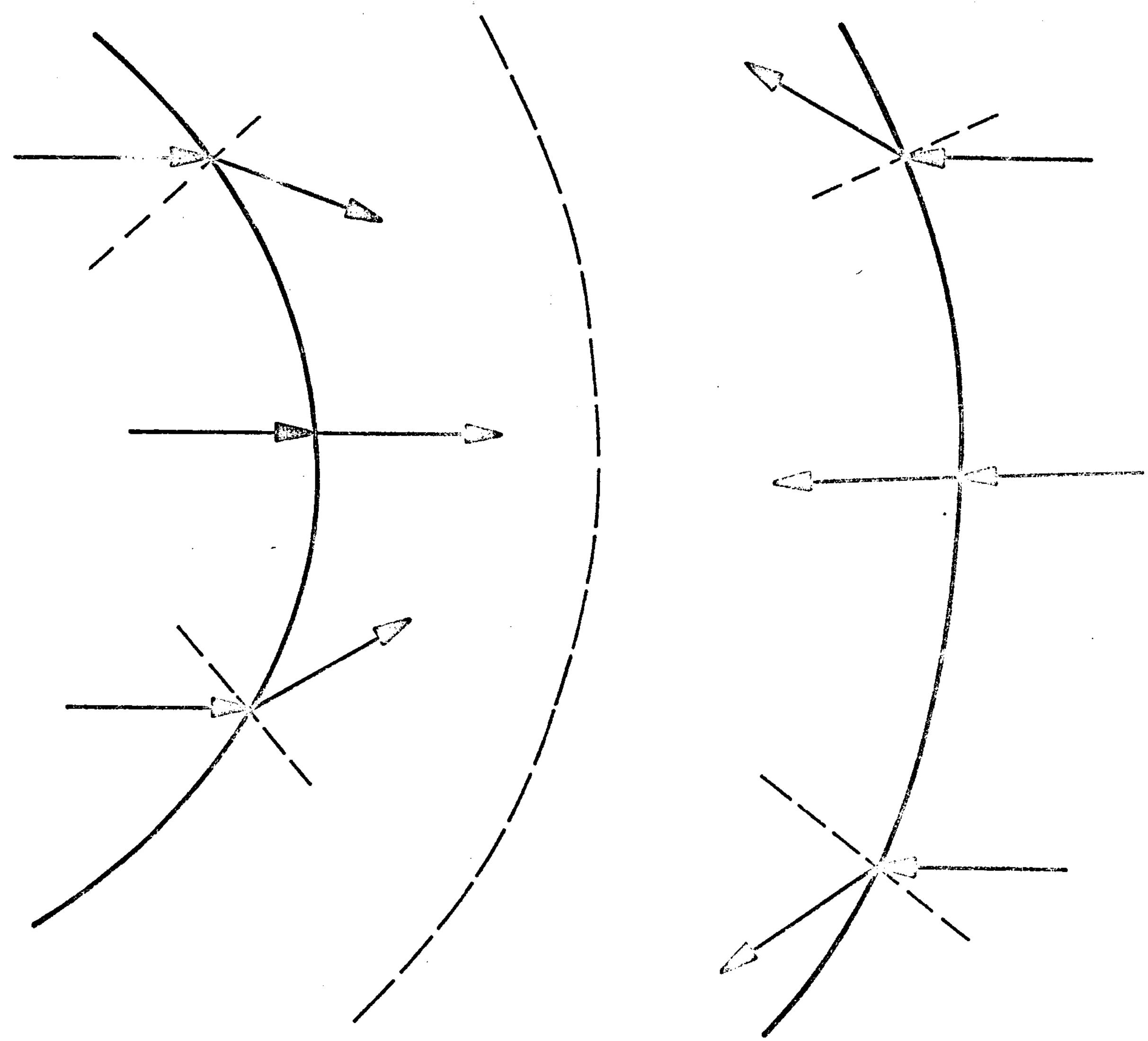
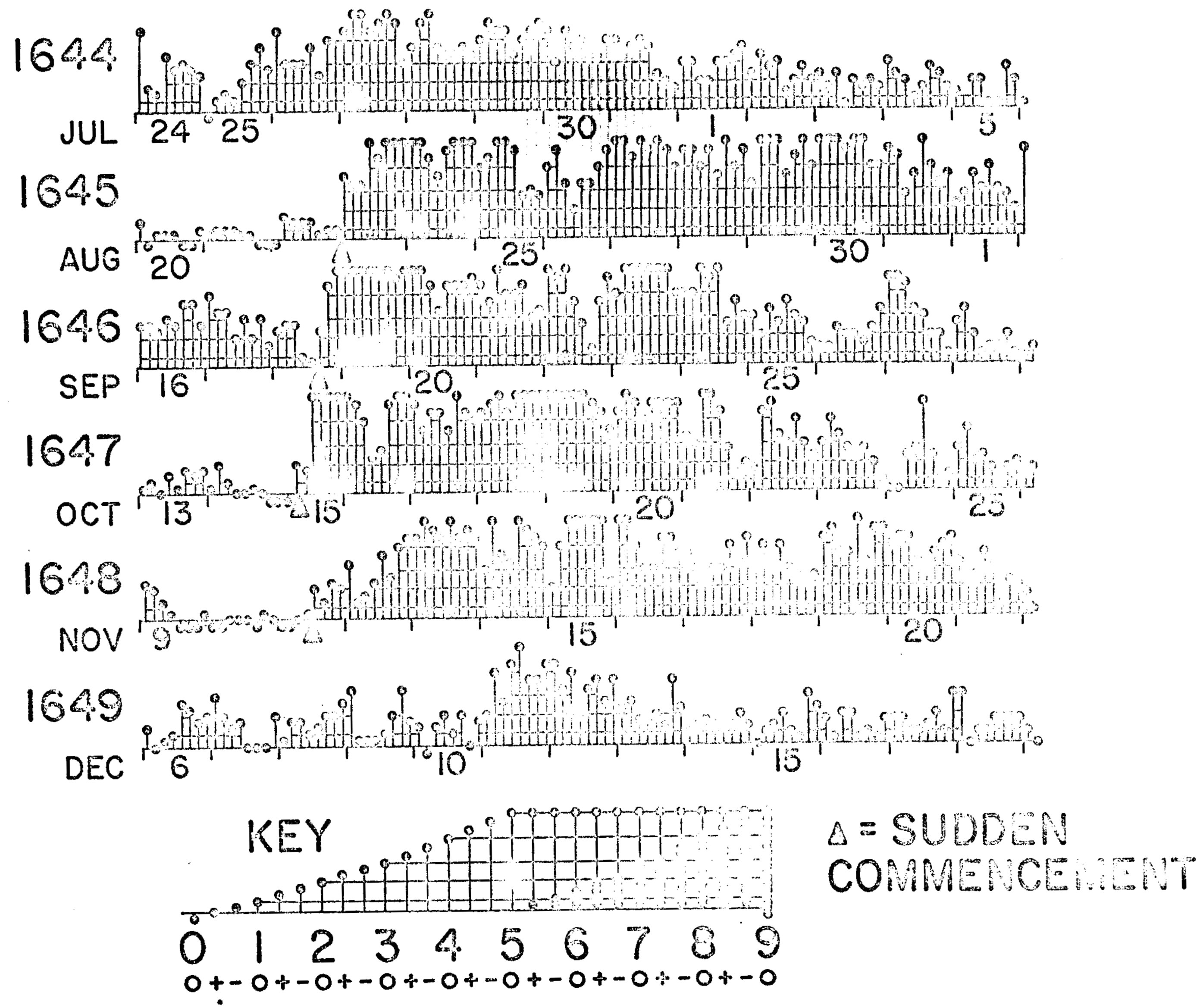


Figure 2



1644
JUL
24
25
30
1
5
1645
AUG
20
25
30
1
1646
SEP
16
20
25
1647
OCT
13
15
20
25
1648
NOV
9
15
20
1649
DEC
6
10
15
KEY
0 1 2 3 4 5 6 7 8 9
o+-o+-o+-o+-o+-o+-o+-o+-o+-o+-o
Δ = SUDDEN COMMENCEMENT

Figure 3

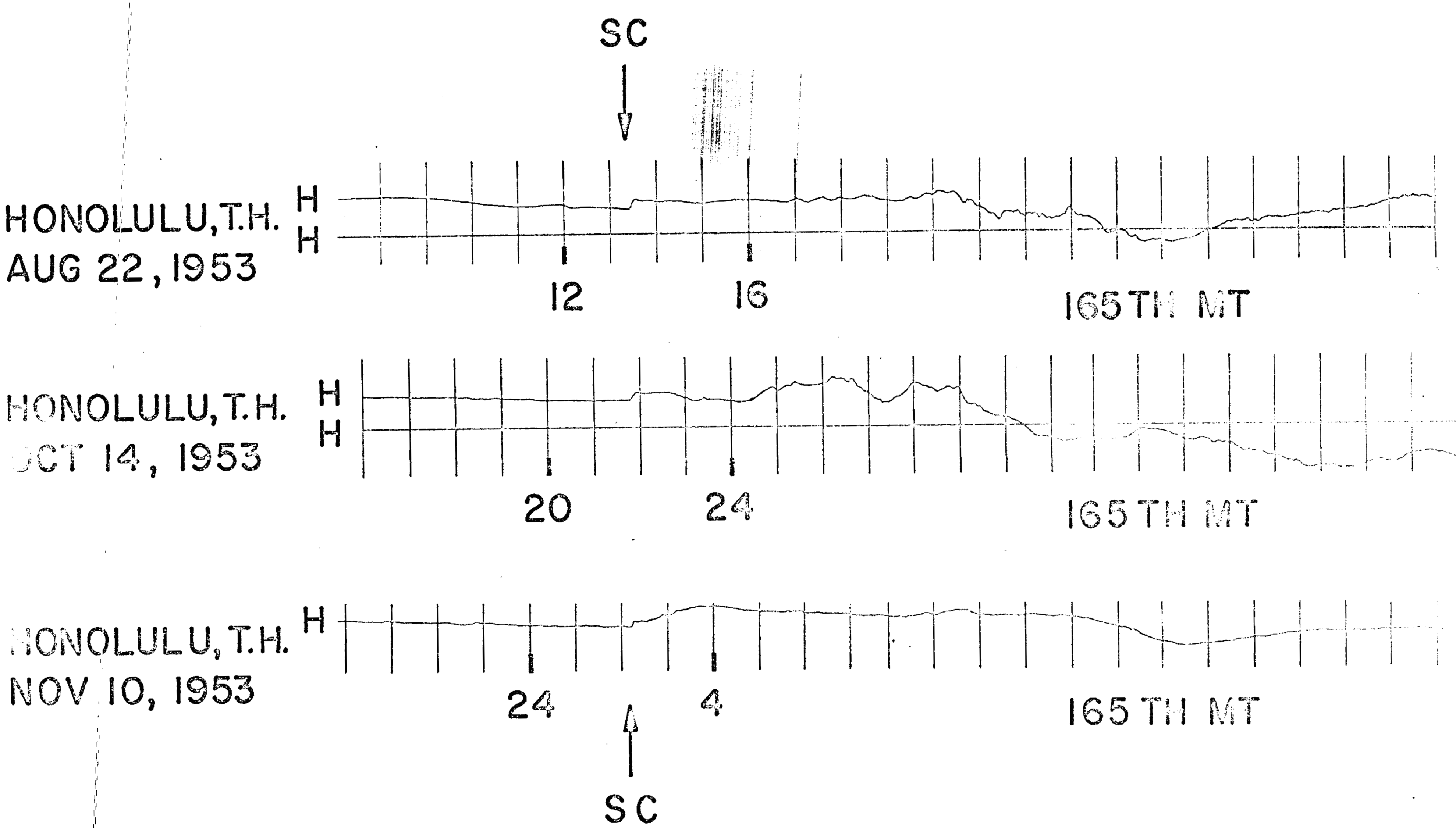
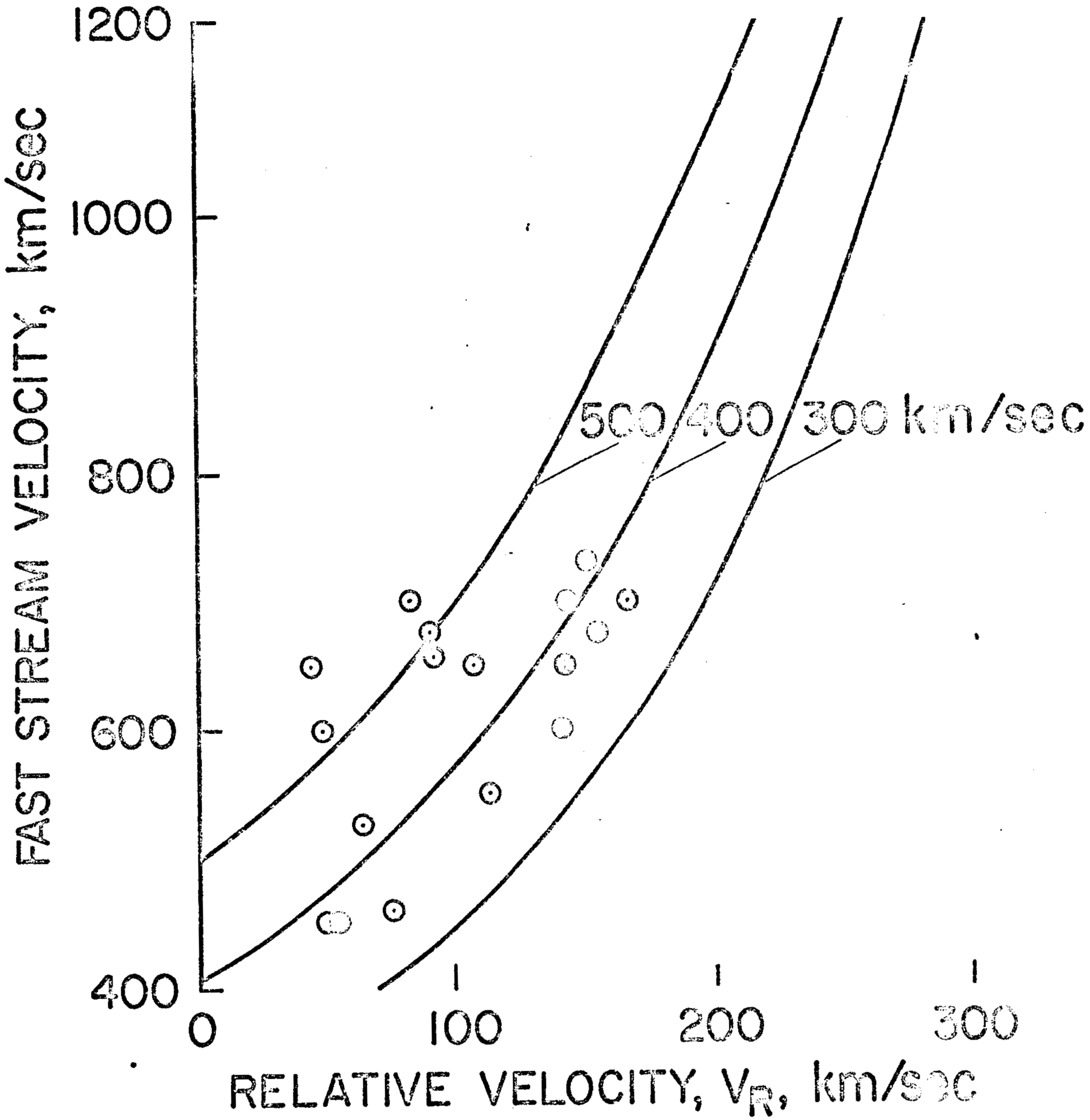

SC
HONOLULU, T.H.
AUG 22, 1953
H
H
12
16
165TH MT
HONOLULU, T.H.
OCT 14, 1953
H
H
20
24
165TH MT
HONOLULU, T.H.
NOV 10, 1953
H
24
4
SC
165TH MT

Figure 4



FAST STREAM VELOCITY, km/sec
1200
1000
800
600
400
0
100
200
300
RELATIVE VELOCITY, V_R, km/sec
500
400
300 km/sec

Figure 5

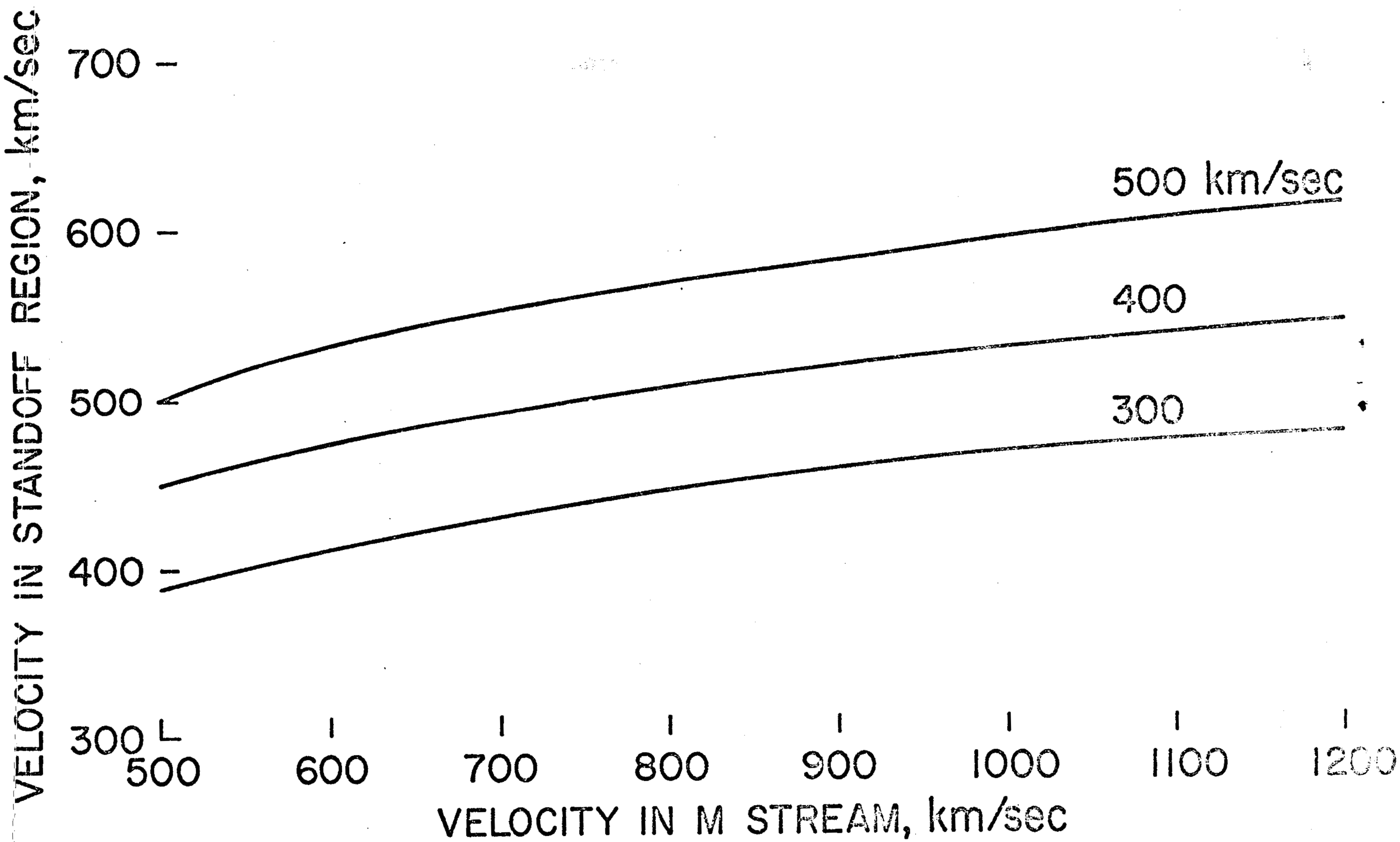

VELOCITY IN STANDOFF REGION, km/sec
700
600
500
400
300
500 km/sec
400
300
500
600
700
800
900
1000
1100
1200
VELOCITY IN M STREAM, km/sec

Figure 6